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Comparison of several models for multi-size bubbly flows on an adiabatic experiment

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ABSTRACT

This paper deals with the modelling and numerical simulation of *isothermal bubbly flows with multi-size bubbles*. The study of isothermal bubbly flows without phase change is a first step towards the more general study of boiling bubbly flows. Here, we are interested in taking into account the features of such isothermal flow associated to the multiple sizes of the different bubbles simultaneously present inside the flow. With this aim, several approaches have been developed. In this paper, two of these approaches are described and their results are compared to experimental data, as well as to those of an older approach assuming a single average size of bubbles. These two approaches are (i) the moment density approach for which two different expressions for the bubble diameter distribution function are proposed and (ii) the multi-field approach. All the models are implemented into the NEPTUNE_CFD code and are compared to a test performed on the MTLOOP facility. These comparisons show their respective merits and shortcomings in their available state of development.

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1. Introduction

This paper deals with the modelling and the numerical simulation of *isothermal multi-size bubbly flows*. Several physical phenomena determine the bubble size and shape, which in turn determines the evolution of the flow structure (void fraction distribution, mean liquid and gas velocity profiles, turbulence intensity in the liquid phase…). The phenomena responsible for the changes in the bubble size distribution are the bubbles coalescence and break-up, the gas compressibility, the phase change and the bubbles deformations. Here, we will assume that the bubbles remain *spherical*, for the sake of simplicity. However, when the bubbles distort (i.e. they do not retain their spherical shape), the interface becomes anisotropic and a full tensorial treatment should be adopted (Doi and Ohta, 1991; Wetzel and Tucker, 1999; Lhuillier, 2004a,b; Morel, 2007). This general approach is very complicated, and only few closures are available in the literature in very restricted cases. Therefore, for this first study, we assume that the bubbles remain spherical. In fact, in all the approaches that will be presented here, the bubbles are supposed to be multi-dispersed in size but not in shape. The general study of bubbly flows with bubbles multi-dispersed in size and in shape could be envisaged in a future work.

It is also assumed that there is no phase change, therefore only the first three types of physical phenomena (coalescence, break-up and gas compressibility) will influence the bubble diameter. Indeed, we consider isothermal flows without phase change as a first stage with the aim of evaluating the different approaches for the prediction of bubbly flows with multi-size bubbles, and that, although some of these methods have already been tested in boiling bubbly flow studies (Seiler and Ruyer, 2008; Morel and Laviéville, 2008).

The simultaneous existence of several bubble sizes in a bubbly flow has direct consequences on the velocities. In a quiescent liquid, it is observed that the bubble rising velocity generally depends on the bubble size: the larger the bubble, the greater the bubble rising velocity. If we consider a more complex flow, with a vertical liquid flow rate, and define the bubble relative velocity as the difference between the bubble velocity and the velocity of the surrounding liquid, this relative velocity depends on the bubble size in the same manner. This difference between the relative velocities of bubbles having different sizes is known as a possible source of bubble collisions and coalescences (Prince and Blanch, 1990). Another important aspect for upward bubbly

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flows in vertical pipes is that the small bubbles move laterally towards the pipe wall, and the large bubbles (above a critical size) move laterally in the opposite sense, i.e. towards the pipe axis. These various behaviours have been observed experimentally by many authors. Tomiyama (1998) relates this behaviour to the change of sign of the lift force, which is responsible for the lateral bubble migration, and proposes an empirical correlation to express the lift coefficient as a function of the bubble diameter (via the bubble Reynolds and Eotvos numbers). These two phenomena illustrate also the fact that a bubbly flow with multi-size bubbles is generally characterized also by bubble multiple velocities. In some approaches, like the multi-field approach presented in Section 6, this multi-velocity aspect can be taken into account in a very natural way but is tacked with more difficulties by other approaches, like with the moment density approaches described in Sections 4 and 5.

This paper is organized as follows. In Section 2, we briefly recall the two-fluid model in its simplified version for isothermal flows without phase change and the evolution equations for the different useful moment densities of the bubble diameter distribution function. All the presented approaches here can be derived from the equations established in Section 2, except for the multi-field approach, whose bases will be detailed in Section 6. Section 3 is devoted to the classical *single-size* approach, in which an *interfacial area concentration* (IAC) evolution equation is included. This IAC is combined with the bubble void fraction to determine the bubble *Sauter mean diameter* (SMD) which is the single diameter considered in this approach, called besides "single size". Two different approaches, namely the *moment's density approach* and the *multi-field one*, are frequently considered for the CFD simulations of bubbly flows with multiple bubble sizes. Two Sections 4 and 5 are devoted to various versions of the moment's density approach, and Section 6 is devoted to the multi-field approach. Simulations of a MTLOOP experiment have allowed comparing results of the various approaches and deducing their merits and shortcomings. This experiment will be described in Section 7. One experimental test is calculated with these four different approaches implemented into the NEPTUNE_CFD code. The results of the comparisons are presented in Section 8. In Section 9, some conclusions are drawn about the present status of the different methods and some perspectives are given for future work.

2. Two-fluid model and geometrical balance equations

In this paper, we deal with adiabatic and isothermal bubbly flows without phase change. In this situation, the mass and momentum balance equations of the two-fluid model read (Ishii and Hibiki, 2006):

$$\begin{aligned} &\frac{\partial\alpha_k\rho_k}{\partial t}+\nabla.(\alpha_k\rho_k\underline{V}_k)=0 && k=L,G\\ &\frac{\partial\alpha_k\rho_k\underline{V}_k}{\partial t}+\nabla.(\alpha_k\rho_k\underline{V}_k\underline{V}_k)=-\alpha_k\underline{\nabla}p_k+\underline{M}_k+\alpha_k\rho_k\underline{g} \\ &\qquad\qquad +\nabla.[\alpha_k(\underline{\underline{\tau}}_k+\underline{\underline{\tau}}_k^T)] && k=L,G \end{aligned} \tag{1}$$

where α_k is the local time-fraction of presence of phase k, ρ_k its averaged density, $\underline{V}_k$ its averaged velocity and p_k the bulk-averaged pressure for phase k. The vector g is the gravity acceleration, $\underline{\underline{\tau}}_k$ and $\underline{\underline{\tau}}_k^T$ are the averaged viscous stress tensor and the turbulent "Reynolds" stress tensor, respectively, and the vector $\underline{M}_k$ is the averaged interfacial transfer of momentum. The phase index k takes the values L for the liquid phase and G for the gas phase. Eqs. (1) have been obtained by Ishii and Hibiki (2006) by means of a time-averaging, but very similar equations can be obtained by means of ensemble averaging (e.g. Drew and Passman, 1999). The difference between the interfacial-averaged pressure for phase k p_{ki} and the bulk-averaged pressure p_k has been neglected. We will also neglect the difference between the two bulk-averaged pressures in the two phases, therefore making the approximation $p_L = p_G = p$.

Making this approximation of a common pressure for the two phases, the closure issue of the system of equations (1) lies in the averaged viscous stress tensors for the two phases, the Reynolds stress tensors for the two phases and the interfacial momentum transfers. Here we will describe only the closure of this last term (see also Section 8). If we neglect the averaged effects of the interfacial tension, the averaged interfacial momentum balance reduces to (Ishii and Hibiki, 2006):

$$\sum_{k=L,G}\underline{M}_k=0 \tag{2}$$

Therefore it is sufficient to express the gas (or liquid) interfacial momentum transfer term, the liquid (or gas) interfacial momentum transfer being deduced from the action and reaction principle, in the context of the assumptions mentioned above. In bubbly flow studies, the interfacial momentum transfer term $\underline{M}_k$ is often decomposed into several averaged forces, namely a drag force, an added mass force, a lift force, a turbulent dispersion force and sometimes a wall force. The averaged expressions of these forces can be obtained approximately by averaging classical expressions for the forces exerted by the liquid on a single spherical bubble (e.g. Morel et al., 2004). These different forces involve the bubble diameter, therefore their averaged counterparts involve some geometrical moments of the bubble diameter distribution function, like the void fraction, the IAC and some averaged bubble diameters. It is therefore necessary to determine these geometrical moments in order to close the interfacial momentum transfer term. It is worthwhile to note that, in more general boiling bubbly flows involving phase change, the IAC or other geometrical variables also strongly influence the heat and mass interfacial transfers, hence the great importance given to their correct modelling.

As the bubbles remain spherical, the geometry of the bubbles population can be completely described by means of a distribution function $f(\xi;\underline{x},t)$ where ξ is a parameter characteristic of the bubble size, such as its diameter, its interfacial area or its volume. The bubble distribution function $f(\xi;\underline{x},t)$ is defined such that $f(\xi;\underline{x},t)\delta\xi\delta^3x$ is the probable number of bubbles having a size parameter between ξ and $\xi+\delta\xi$ into the volume element δ^3x around the point $\underline{x}$ at time t. Here we choose the bubble diameter d being the parameter ξ. The mean geometry of the bubble population can also be derived from the statistical moment densities of the distribution function. The pth-order moment density of the diameter distribution function is defined by:

$$S_p(\underline{x},t)\ \hat{=}\ \int d^pf(d;\underline{x},t)\delta d \tag{3}$$

We can construct an infinite number of mean diameters d_{pq} by using an infinite number of moment densities, through the definition relation:

$$d_{pq}\hat{=}\left(\frac{S_p}{S_q}\right)^{\frac{1}{p-q}} \tag{4}$$

The first four moment densities are related, under some assumptions regarding their spatial variation, to very useful quantities for the study of bubbly flows with spherical bubbles:

$$n\ \hat{=}\ S_0,\quad d_{10}\ \hat{=}\ S_1/n,\quad a_i\hat{=}\pi S_2,\quad \alpha\hat{=}\pi S_3/6 \tag{5}$$

where $n(\underline{x},t)$ is the bubble number density, $d_{10}(\underline{x},t)$ is the mean bubble diameter (mathematical expectation), $a_i(\underline{x},t)$ is the interfacial area concentration (IAC) and $\alpha(\underline{x},t)$ is the void fraction (averaged volumetric fraction of the gas phase). Three other important mean diameters are often used:

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