Mean motion induced in a liquid by rising bubbles

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Summary We report experiments on the mean motion generated by a uniform injection of bubbles in a uniform liquid flow. The Reynolds number of the relative motion is high, the Weber number is moderated and the void fraction is varied up to 15%. With a newly developed methodology, we estimate the statistics of the liquid velocity conditioned or not by the presence of the bubbles. We therefore discuss the displacement of liquid induced by the relative motion of the bubbles. We discuss drift flux models as developed by Kowe *et al* (1988) and more recently by Eames *et al* (2003). An attempt to take into account wakes effects in such models is also presented.

INTRODUCTION

The present problem is related to the characterisation of the mean motion induced in the liquid phase of a homogeneous flow by the relative movements of a swarm of ascending bubbles. Our purpose is to get insight into the complex mechanisms of transport in the liquid phase of a bubbly flow, using precise and well suited definitions of the statistical properties of the flow. We focus on the analysis of inertial bubbly flows at large Re (typically Re=200), and moderate We (We=0.4-0.6). In this work we distinguish between statistics in the liquid conditioned or not by the presence of the bubbles. We develop a global methodology to define the separation between the statistics of the local velocity field perturbed by an individual bubble (strongly controlled by the local boundary condition even though it can also be influenced by hydrodynamics interactions), and the far-field statistics where hydrodynamic interactions entirely control the velocity field. Such a distinction allows us to analyze drift mechanisms, and to discuss the definition of the mean relative velocity between both phases. We examine the mechanistic drift flux model developed by Kowe *et al*. (1988), and the recent analysis by Eames *et al*. (2003). We present a comparison between new experimental results and model predictions. An attempt to take into account the effect of entrainment by the wakes in such models is also discussed.
The experimental set-up is described into details in Larue de Tournemine (2001). A uniform bubbly flow is generated in a vertical channel of 3.1 m height and 0.3 x 0.15 m^2 cross-sectional area. The gas flow rate can be varied from $Q_G = 2.52\ 10^{-4}$ m^3s^{-1} to $Q_G = 3.6\ 10^{-3}$ m^3s^{-1}. While the liquid flow rate is maintained constant all along the experiments ($Q_L = 18.2\ 10^{-3}$ m^3s^{-1}), we vary the void fraction from 0.3 % to about 14 %, by varying the gas flow rate. We have used hot film anemometry to measure the velocity of the liquid. Precise tests proved that we can be self-confident in the meaning of the hot film anemometry signal in the vicinity of the interfaces. The mean bubble diameter varies from 1.14 mm to 2.38 mm depending on Q_G . Double optical fibber probes (OFP) were used to measure bubble sizes and bubbles velocities.

MOTION OF THE LIQUID IN THE VICINITY OF THE BUBBLES

Phase average

We have calculated the average form of the velocity field in the liquid phase in the neighborhood of the bubbles by a phase averaging of the velocity signals obtained from hot film anemometry around each detected bubble. We use two phase averages, a downstream one and an upstream one, denoted $\langle U(\tau)\rangle$,with the upstream and downstream detected interfaces respectively as reference points of these averages. Whatever the void fraction, the phase average shows that the perturbation of the velocity field due to bubble passage is mainly potential at the front and controlled by the wake at the back of the bubble (Figure 1). The distance necessary to recover the asymptotic level at infinity is higher in the rear field than in the upstream field. Far away from the bubble interfaces, the velocity reaches an asymptotic level, independent of the distance from the bubble. The far field is, thus, not controlled by the action of the test bubble, and controlled by hydrodynamic interactions.

Characteristic length scales of the flow around the bubbles

It is difficult to compare the profiles of the phase averages with models of relative motion around an isolated bubble because the phase average integrates combined effects of several random processes (piercing, random angle between vertical and trajectory, diameter). Nevertheless we have defined characteristic time (or length) scales for the decrease of the perturbation on each side of the bubble. While the time scale upstream is quite independent of the void fraction, the time scale downstream decreases when the void fraction increases. The decrease is consistent with the observation made by Risso & Ellingsen (2001), who found, at low void fraction, that the hydrodynamic interactions make the liquid velocity decrease faster downstream of a bubble in a suspension than in the wake of an isolated bubble. It is also consistent with a recent theoretical analysis of Hunt & Eames (2002) showing that the external strain exerted on the wake due to the blockage effect of the neighboring bodies leads to a rapid disappearance of this wake in two-phase flows.

CONDITIONAL AVERAGES

These time scales give the extend of the perturbation induced by the bubble passages. The analysis of the phase average thus allows us to define conditional averaging of the velocity of the liquid in the near field and in the far field of the bubbles passing across the point of measurement. The near field average (U_{NF}) is taken over the ensemble of measurements in the liquid phase around each bubble in the part of the signal limited by the relaxation times of the phase average. The far field average (U_{FF}) is taken over the residual signal. The far field average is interesting because it represents the interstitial velocity. It is a concept present in the drift flux models and it allows the estimation of a more significant relative velocity.

DISCUSSION OF DRIFT FLUX MODELS

The eulerian mean velocity U_L which is measured, as well as the measured void fraction, allows to estimate $U = (1-\alpha)U_L$ the local superficial velocity of the liquid. In our experiments, we have also measured the eulerian interstitial mean velocity U_{FF}. We have also measured the velocities of the bubbles. So we can test the predicted links between the variables given by Kowe *et al* (1988) (equation (1)) or by Eames *et al* (2003) (eq. (2)).

$$\frac{(U-U_{FF})}{(V_B-U_{FF})} = \alpha C_M - \frac{\alpha U_{FF}}{V_B-U_{FF}} \qquad (1)$$

$$\frac{(U-U_{FF})}{(V_B-U_{FF})} = \alpha(1+C_M) \qquad (2)$$

where C_M is the added mass coefficient.

The comparison with the model developed by Eames *et al* shows a very good agreement at low void fraction (Figure 2). The model of Kowe *et al* is less satisfactory, may be because it neglects the hydrodynamic interactions. At higher void fraction, the comparison is less satisfactory, because wakes effects cannot be neglected and they are not present in the model of Eames *et al*. built on potential flow approximation. A preliminary attempt to take into account the effects of the vanishing wakes observed in our experimental conditions has been made. The vanishing wakes may be represented in the potential calculus of Eames *et al*. as dipoles whose strength is calculated with the measured relaxation lengths of the wakes. The corrective effect seems quite promising.

CONCLUSIONS

We have developed a method for the analysis of conditional statistics of the velocity in the liquid phase of a bubbly flow. We have defined statistics far away from the interfaces from one-point measurements. This method is quite general and allows a discussion of fluid displacement models. The drift concept and models which up to now had been tested in relatively pure situations of isolated bubbles has been examined in this work in a more complex situation.

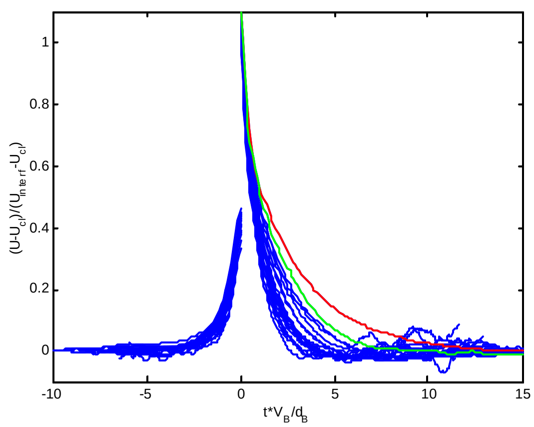

Figure 1 : Phase average of the velocity around the bubbles (red : minimum void fraction ; green, then blue : void fraction increases)

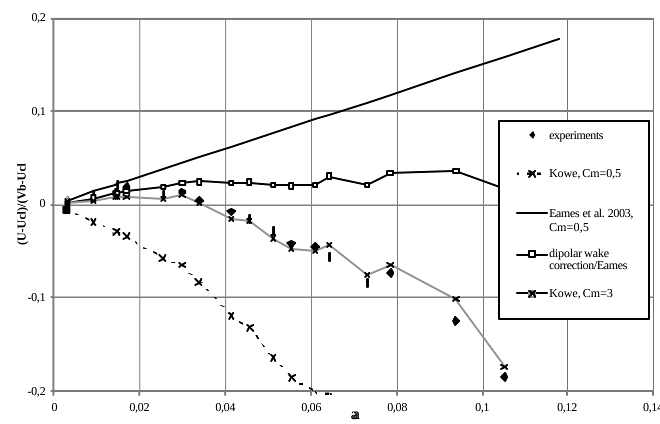

Figure 2 : Comparison between drift models and experimental results (Ucl denotes U_{FF})

(V_b velocity of the bubbles, d_B their diameter , U_{interf} :velocity of the liquid at interface, U_{cl} :at infinity, α void fraction)

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