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Experimental investigations on rising bubbles in stagnant water in vertical capillaries

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We investigate how the walls of cylindrical capillaries affect the velocity of rising gas bubbles of various diameters. Of course, as the capillary diameter increases, the velocity of the rising bubble will approach the case of free rising. Such systematic experiments on the bubble rise in capillaries, in which the ratio of bubble diameter and capillary diameter is varied from one towards smaller values, can hardly be found in literature. Experiments within the system water/air have been conducted in stagnant water and will be discussed in this paper.

1 Introduction

While the free rise of gas bubbles in a liquid has been extensively studied, the rise of gas bubbles in capillaries, i.e. in presence of walls, is almost unexplored. Only the so–called Taylor bubbles, i.e. bubbles so large that they almost fill the capillary cross section, have been studied to a reasonable degree. To optimize devices with bubbles in the range between free rising and Taylor bubbles, it appears essential to derive models that describe the bubble rise in presence of nearby walls. In this work we experimentally investigate how the walls of cylindrical capillaries reduces the rising velocity of gas bubbles. The system of air bubbles in water is used for the investigations, as it is frequently present in biological or chemical sytems. The capillary diameter and the volume of the bubbles are varied to determine the influence of the bubble size onto the rising velocity.

2 Experimental setup

The aim of this work is to investigate the rising velocity U_B of gas bubbles in capillaries as a function of their equivalent diameter d_{eq}. The equivalent diameter d_{eq} is the diameter of a sphere of equal volume. A schematic drawing and an explanation of the entire experimental setup can be found in [1]. After the bubble generation within a calibration capillary, the bubble is transported to a metal needle. The needle is used to inject the bubble into the rising capillary of diameter D. However, when producing larger bubbles, the bubbles often break up at this needle, resulting in two or more smaller bubbles. To prevent this, a construction, shown in Figure 1, is installed that holds back the bubbles. Under a spoon the smaller bubbles can collect and coalesce to a larger bubble. The spoon is then carefully turned over and the large bubble can rise into the capillary. As the gas bubble then rises in the glass capillary, which is filled with stagnant water, the bubble passes through two laser light sheets and the rising velocity is determined by measuring the time difference between the passage of the gas bubble through these two laser sheets (cf. [1]).

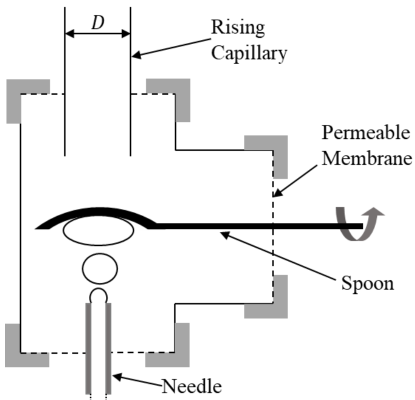

Fig. 1: Schematic drawing of the spoon construction to produce larger bubbles.

3 Results

The determination of the rising velocity U_B of the bubbles is carried out in two different rising capillaries, of diameters $D = 8$ mm and $D = 4$ mm. Several measurements are made for each bubble diameter and an error calculation according to Nalimov [2] is subsequently performed. The results, ignoring the outliers, are shown in Figure 2. While the first results of these measurements are presented in [1], the modified design of the experimental setup now allows for larger bubble diameters $d_{eq} > 3.4$ mm. Here, the rising velocity U_B is plotted against the equivalent diameter d_{eq} of the bubble. The model for free rising bubbles in contaminated water according to Tomiyama et al. [3] is shown as a solid line. To obtain a clear presentation of the results, the diameters are divided into classes of $\Delta d = 0.2$ mm and each diameter class is averaged. Together with the averaged velocity, two graphs are obtained. As already discussed in [1], wall effects can be neglected for small bubble diameters and the rise of these small bubbles appears comparable to the rise in an infinitely–extended liquid. In contrast, for

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larger bubbles, the wall affects the rising velocity of the bubbles substantially. However, buoyancy remains to be the dominating force even if the bubble diameter increases. Beyond the maxima of both curves, the influence of the wall effect becomes stronger, such that the rising velocity decreases as the bubble diameter increases. Both curves show the significant scatter of the data near the maxima, as already mentioned before in [1]. As already discussed in [1], Tomiyama [4] confirms the faster rise of deformed bubbles and suspects an effect of the initial deformation of the bubbles during the formation at the needle. Though, we cannot confirm this relationship in our experiments, we are able to confirm characteristic differences in the bubble formation, but these only depend on the bubble diameter. However, our experiments do not show any dependence of the rising velocity on this initial deformation. Following the curves to larger bubbles, particularly the $4\ \mathrm{mm}$ capillary can be blocked by the bubble. The equivalent diameter d_{eq} for this event corresponds approximately to the capillary diameter D. This blocking of the capillary does not occur within the $8\ \mathrm{mm}$ capillary, but for this larger capillary a different phenomenon occurs. As an equivalent bubble diameter of $8\ \mathrm{mm}$ is approached, a short increase of the rising velocity can be recognized, followed by a secondary drop of the curve for increasing bubbles. Figure 3 shows a magnification of this curve and the associated images. The first image shows a bubble with pronounced deformation in the lower region, which also pulsates from left to right. These deformations and pulsations decrease with increasing bubble diameter. From a bubble diameter of a little more than $8\ \mathrm{mm}$, the bubbles exhibit an elongated shape. An explanation for this behavior can be found in the flow around the bubble during its rise. Due to the mobile interface of the bubble in the first image, the cross section between the capillary wall and the bubble is repeatedly narrowed. As a result, the downward flow of the water around the bubble is impeded and the rising velocity decreases. As the interface stabilizes with increasing equivalent diameter, these fluctuations decrease and the flow profile along the bubble stabilizes. Hence, the rising velocity increases again. For larger bubbles, the free cross section further decreases, so that the velocity of the water flow around the bubble increases, leading to a further slow down of the bubble rising velocity. Once a minimal free cross section is reached, as the equivalent diameter increases further, the bubble elongates. Hence, a minimal rising velocity is approached. This behavior of the curve essentially reflects the transition from roughly–spherical bubbles to striking elongated bubbles, so–called Taylor bubbles.

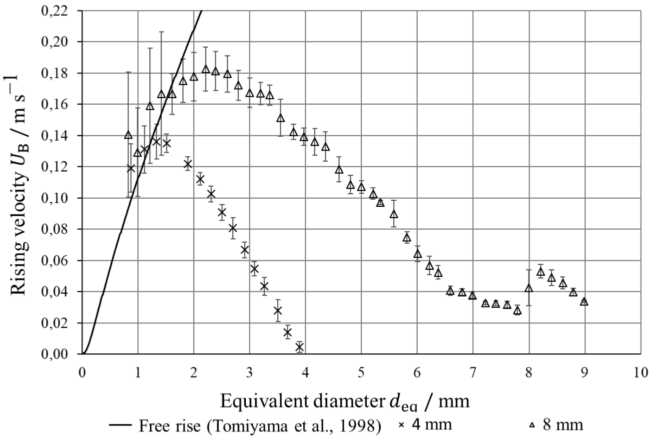

Fig. 2: Measured velocities U_B (symbols) are plotted against the bubble equivalent diameter d_{eq} of the bubbles. The model of free rising bubbles in contaminated water according Tomiyama et al. [3] is shown as solid line.

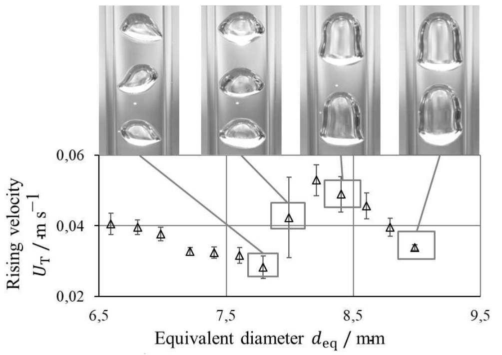

Fig. 3: Transition from reasonably spherical bubbles to so–called Taylor bubbles.

4 Conclusion and future works

With the introduction of a spoon construction, larger bubbles could be generated, extending our investigations to larger equivalent bubble diameters. Measurements were performed with capillary diameters of $D = 8\ \mathrm{mm}$ and $D = 4\ \mathrm{mm}$. All measurements of the bubble rising velocity show a maximum, beyond which the wall effect dominates the system. As a consequence, the bubbles are slowed down with increasing equivalent bubble diameters. The statement of Tomiyama [4], that the scatter of measured data near the curve of free rising, depends on the bubble deformation during formation, could not be verified by recording the bubble formation with a high–speed camera. Instead, by means of these optical methods we find that in the $D = 8\ \mathrm{mm}$ capillary, for larger bubbles, a transition from deformed bubbles to so–called Taylor bubbles can be observed. This transition appears to be responsible for the strange behavior of the bubble rising velocity. Furthermore, more experiments with other capillary diameters, as well as with co–current and counter–current flow of the surrounding liquid are presently in progress. Here again, the bubble shape in all capillaries and for all flow regimes are recorded and carefully analyzed.

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