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Experimental investigations on rising bubbles 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 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. First orienting experiments within the system water/air have been conducted 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. with walls is almost unexplored. Only the so-called Taylor bubbles, i.e. bubbles so large that they almost fill the capillary cross section, has been studied to a reasonable degree. In order to optimize devices in the range between free rising and Taylor bubbles, it appears essential to derive models that describe the bubble rise with wall influence. In this work we investigate how the walls of cylindrical capillaries reduces the rising velocity of gas bubbles. The system of air bubbles in water is used as the system investigations, as it is frequently present in the biological and chemical industry. The capillary diameter and the volume of the bubbles are varied in order to determine the influence of the bubble size on the rising velocity.

2 Experimental setup

The aim of this work is to investigate the rising velocity U_B of gas bubbles as a function of their equivalent diameter d_{eq}. The equivalent diameter d_{eq} is the diameter of the sphere of equal volume. A schematic drawing of the experimental setup is shown in Figure 1. Within a calibration capillary of diameter $D_{cal} = 0.4\,\mathrm{mm}$, the gas bubble, which will later rise in the rising capillary, is generated. A water syringe is connected with a tube to the lower end of the calibration capillary. The calibration capillary also has a bore in which a cannula is airtightly glued in with silicone glue. This cannula is connected to the air syringe. In addition, a measuring scale is fixed to the calibration capillary in order to infer the bubble volume from the length of the gas bubble in the calibration capillary. After the gas bubble has left the calibration capillary, it is transported through the PTFE tube. This is connected to a metal needle, which is used to inject the bubble into the rising capillary of diameter D. The gas bubble rises in the glass capillary, which is filled with water. It is clamped vertically inside a Plexiglas box. This Plexiglas box is filled with deionised water. This enables a stable temperature control. When the gas bubble rises, it passes through two laser sheets. The rising velocity is determined by measuring the time difference between the passage of the gas bubble through the two laser sheets.

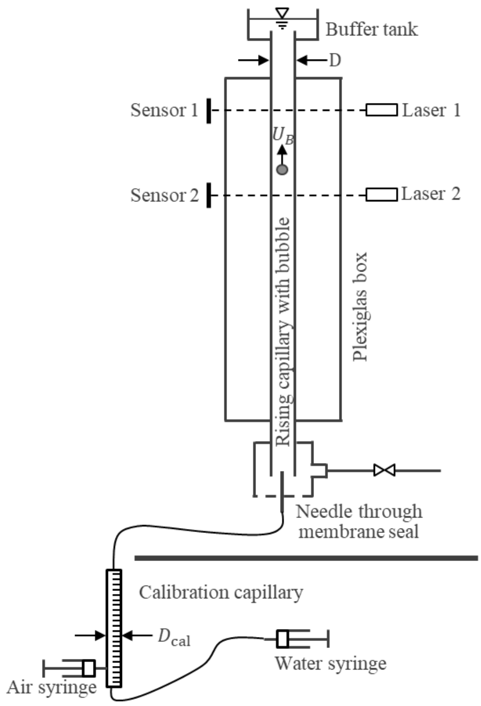

Fig. 1: Schematic drawing of the experimental setup.

3 Results

The determination of the rising velocity of the bubbles is carried out in two series with two different rising capillaries. In measurement series 1, the diameter of the rising capillary is $D = 8$ mm. In measurement series 2, the diameter of the rising capillary is $D = 4$ mm. Several measurements have been taken for each bubble diameter. An error calculation according to Nalimov [1] is performed with the results. The results, neglecting the outliers, are shown in Figure 2.

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The rising velocities U_B are plotted against the equivalent diameter d_{eq} of the bubble. In addition, the model for free rising bubbles in contaminated water according to Tomiyama et al. [2] is shown as a solid line. Both series of measurements approach for small ratios of the bubble to capillary diameters the curve for the free rising. For measurement series 1 this applies up to $d_{eq} = 1.7$ mm and for measurement series 2 up to $d_{eq} = 1.2$ mm. In these ranges, wall effects are hardly visible. Furthermore, a velocity maximum occurs for larger diameters. In measurement series 1 this is at a bubble equivalent diameter of $d_{eq} = 2.05$ mm, and in measurement series 2 at $d_{eq} = 1.4$ mm. From these points on, the wall influences play an important role. For series 2, it can be seen that from the maximum, the velocity drops continuously. In contrast, in series 1 the gradient initially decreases, but is followed by an increase so that the velocity becomes almost constant.

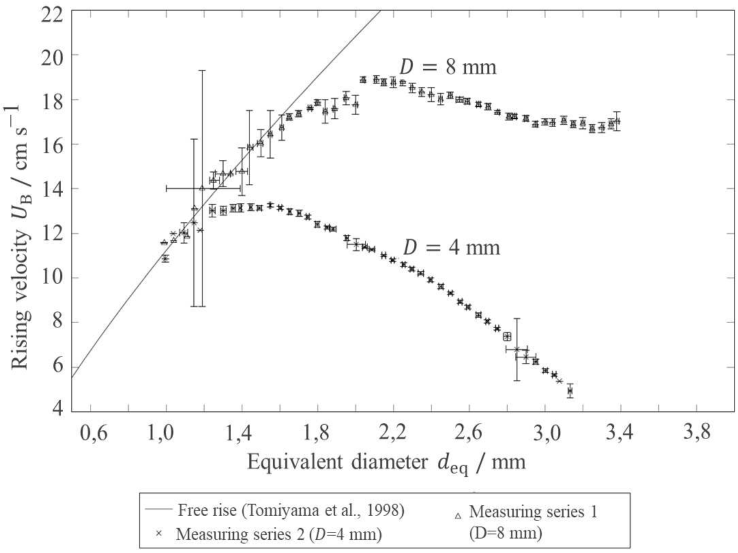

Fig. 2: The velocities U_B are plotted against the bubble equivalent diameter d_{eq} of the bubble. The model of free rising bubbles in contaminated water according Tomiyama et al. [2] is shown as a solid line.

In the ranges where the measured values leave the curve of free rising, a quite large standard deviation results from the scattering of the measurments. Tomiyama [3] attributes this to different deformations at the time of bubble generation. A correlation between the rising path and the measurement could not be detected by the naked eye and should be investigated by optical methods. Another explanation for the downward scattering could be that the gas bubbles approach the wall during rising. Since the relative velocity is lower there due to the no-slip condition at the wall, the lower velocity could be explained. This phenomenon occurs especially in measurement series 1, because in this series the larger capillary diameter was used. The consequence of this is that the rising bubble has more space and may not rise centrally. The trajectories, therefore can deviate substantially from a straight line. In addition, the bubbles in measurement series 1 can deviate more strongly from the spherical shape. This is particularly true for ratios of the bubble to capillary diameters close to one. This leads to circulation and consequently to a smaller wall distance, which in turn ensures that the bubble rises more slowly than the others. For measurement series 2 this effect is reduced, because the wall effects rather ensure that no oscillation occurs within the capillary. The upward scattering can be explained similarly. Since the bubbles in measurement series 2 are smaller in the range of the high points, a larger capillary force acts due to the smaller radius of curvature, which stabilizes the bubble. The consequence is that the bubble is less deformed at the time of formation. The rising velocity therefore is lower.

4 Conclusion and future works

With the aid of two laser sheets, the rising velocity of air bubbles in capillaries filled with water could be investigated. The measurements were performed with a capillary diameter of $D = 8$ mm and $D = 4$ mm. The measurements of the velocity show a maximum, beyond which the wall effects dominates the system. As a consequence, the bubble is slowed down more strongly with increasing equivalent diameter. The measurements are scattered in the ranges where the they leave the curve of free rising. According to Tomiyama [3], the origin of the scattering is that the bubbles are deformed to different degrees at the time of generation. This could be verified by recording the bubble generation with a high-speed camera. This method offers the advantage that additionally the trajectory of the bubble during its rise can be reconstructed. Thus, it could be checked whether there is a correlation between the scattering and a wall contact. Since the behaviour of the capillary from measurement series 1 was only investigated up to an equivalent diameter of $d_{eq} \leq 3.4$ mm, it is reasonable to extend the range. This cannot be achieved with the current design, as the needle opening does not allow the formation of larger bubbles. It is advisable to use a larger needle for bubble injection, since the size that can be generated depends on the diameter of the injection port. An alternative method would be to collect several bubbles under an inverted cup. This large bubble could be introduced into the capillary by turning the cup upwards. By knowing the individual bubble volumes, the equivalent diameter of the detected bubble can be deduced. In addition, it appears essential to examine further capillary diameters.

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References

[1] V. V. Nalimov, The application of mathematical statistics to chemical analysis, Pergamon Press, Oxford (1963).

[2] A. Tomiyama, I. Kataoka, I. Zun, and T. Sakaguchi, JSME International Journal Series B 41(2), 472–479, (1998).
[3] A. Tomiyama, Single bubbles in stagnant liquids and in linear shear flows (2002) In: Workshop on Measurement Technology (MTWS5), FZ Rossendorf, Dresden, Germany. S. 3-19.

